Exposure Minimization Algorithm in Homogeneous Indoor Networks

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***Abstract*—Due to the increased use of indoor wireless networks and the concern about human exposure to the RF sources, there is a need for network planners for exposure-aware network planning. A heuristic exposure minimization algorithm for indoor WiFi networks is presented and applied to an actual office building. The exposure characteristics of an exposure-optimized network are compared with those of a traditional network deployment.**

***Index Terms*—human RF exposure, optimization, exposure, exposure reduction, WiFi, reduction, minimization, exposure minimization, green**

I. Introduction

Due to the increased popularity of indoor wireless networks, many software tools have been developed for the prediction of the received signal quality and the network performance. In [1], the authors presented the WiCa Heuristic Indoor Propagation Prediction (WHIPP) tool, a heuristic indoor propagation prediction tool, which is able to design and optimize a Wireless Fidelity (WiFi) network for a given coverage requirement with a minimal number of access points (APs).

In the meanwhile, both the trend towards green networking [2] as well as the enormous increase of wireless communication due to the increasing need for coverage and high data rates, make it necessary to investigate and characterize the exposure of the general public to electromagnetic fields at RF (radio-frequency) frequencies used for wireless telecommunication. Measurements and studies have indicated that indoor exposure cannot be neglected [3]. International safety guidelines such as ICNIRP (International Commission on Non-Ionizing Radiation Protection) [4] have been developed and authorities and countries have implemented laws and norms to limit human exposure [5]. This indicates the need for an accurate exposure characterization and exposure-aware network planning. Consequently, research has recently been started on *green* network deployments. Besides attempts to limit energy consumption in wireless (access) networks [6], the concerns about a possible harmful impact of human exposure to RF sources have led to a situation where network planners (out of necessity) have to take the field strength of the incident waves into account.

However, most research still focuses on the mere *determination* of RF exposure in different environments and/or for different technologies [7]–[10], without focusing on an actual reduction or minimization of the exposure. Other studies try to predict or simulate the 'impact' of a deployment, e.g., in [11]. Green networks [12] or networks with a low environmental impact [13] are often obtained based on genetic algorithms. Both papers [12], [13] are aimed at outdoor environments, often for which simple propagation models are used, permitting the usage of genetic algorithms, due to the short calculation time of a single iteration.

Due to the more complex prediction models used in the WHIPP tool, a heuristic approach is followed for the indoor exposure minimization algorithm that will be presented here. It will be applied to a homogeneous 2.4 GHz WiFi network in which a WiFi receiver is located (e.g., a laptop or a mobile phone) is located in an office building. A homogeneous network is a network where the receiver can only connect to transmitters of one single technology. For the homogeneous scenarios considered here, we will also assume that there are no transmit devices of other technologies present in the building. In Section II, the exposure model will be constructed and validated. Section III will discuss the exposure minimization algorithm, followed by an analysis of the application of the algorithm to an office building in Section IV. In Section V, the conclusions of this paper are presented.

II. Construction and Validation of the Exposure Model

In this section, the model to predict the electric-field strength caused by a transmitter will be derived. In [14], a far-field conversion formula between path loss and electric-field strength is presented.

$$\mathrm{PL}\,[\mathrm{dB}] = 139 - \mathrm{E}_{\mathrm{ERP=1kW}}\,[\mathrm{dB}\mu\mathrm{V/m}] + 20\cdot\log_{10}(\mathrm{f})\,[\mathrm{MHz}], \quad (1)$$

with PL [dB] the path loss between the transmitter and a receiver at a certain location, $\mathrm{E}_{\mathrm{ERP=1kW}}$ [dBμV/m] the received field strength for an ERP (Effective Radiated Power) of 1 kW, and f [MHz] the frequency. Using equation (1) and the identity

$$\mathrm{E}\,[\mathrm{V/m}] = \mathrm{E}_{\mathrm{ERP=1kW}}\,[\mathrm{V/m}] \cdot \sqrt{\mathrm{ERP}\,[\mathrm{kW}]}, \quad (2)$$

and knowing that for dipoles ERP [dBm] = EIRP [dBm] - 2.15, we obtain the following formula for the electric-field strength E [V/m] at a certain location, as a function of the EIRP, the path loss, and the frequency:

$$E\ [\mathrm{V/m}] \;=\; 10^{\frac{\mathrm{EIRP\ [dBm]}\ -\ 43.15\ +\ 20\cdot\log_{10}\ (f)\ [\mathrm{MHz}]\ -\ \mathrm{PL\ [dB]}}{20}}, \tag{3}$$

For the path loss PL of equation (3), the extensively validated WHIPP model of [1] is used. The assumed duty cycle is 100% (worst-case scenario).

The electric-field model of equation (3), with the PL calculated according to the WHIPP model, has also been validated in the proximity of a WiFi access point, with simulations and measurements. It has been shown in [15] that the WHIPP model is a very good approximation for both the *measured* and *simulated* near-field electric-field strength.

III. Exposure Minimization Algorithm

In this section, we will first present the metric that will be used for exposure minimization, followed by a description of the algorithm itself.

A. Optimization metric

There exist different metrics to assess, limit, or minimize the exposure on a building floor, e.g., [11], [12]. In this paper, we will use $\mathrm{E_M}$, the average of the median electric-field strength $\mathrm{E_{50}}$ in the entire building, and the 95%-percentile value $\mathrm{E_{95}}$ of the field strengths in the building.

$$\mathrm{E_M} \;=\; \frac{\mathrm{E_{50}} + \mathrm{E_{95}}}{2}, \tag{4}$$

with the restriction that a certain required coverage has to be provided in the different rooms of a building floor. We chose to include $\mathrm{E_{50}}$ into the metric to account for the median exposure on the building floor, and also $\mathrm{E_{95}}$, to account for the maximal exposure values. We do not just aim to provide a certain coverage, we try to do this in a way that is optimal with respect to human exposure. To calculate the electric-field strength at a certain location, we will only consider the electric-field strength caused by the most dominant source (i.e. the source causing the highest electric-field value at that location). Finally, for the calculation of the cdf of all electric-field strengths throughout the building, we will exclude the locations that are within 30 cm from the transmitters, because we can assume that people will not remain within a 30-cm range of the transmitter for more than a few seconds.

B. Algorithm

The algorithm strives to minimize the *global* exposure metric $\mathrm{E_M}$ on a building floor. Consequently, a larger number of access points will be needed, but their transmit power will be lower. The exposure minimization algorithm consists of four phases.

1) In the first phase, a network containing low-power access points with an EIRP of 1 dBm, is created. This is done according to the optimization algorithm presented in [1]. This yields a network that covers the building floor according to the user's throughput requirements and with the given AP transmit power of 1 dBm. A network with many low-power transmitters is obviously preferred over a network with few high-power transmitters (that still provides the same coverage though), due to the better exposure characteristics of the former network.
2) In a second phase, it is investigated if access points within 125% of their free-space range from each other, can be merged into one new access point (with a possibly higher transmit power). Practical experience has learned that the value of 125% is high enough to not exclude possibly mergeable access points, but not too high to needlessly investigate all access pairs. The merging of two access points is only executed if the value for the *global exposure* metric $\mathrm{E_M}$ is lower for the new network. The access point pairs with the lowest separation between each other are first investigated, because they have the greatest probability of being merged. When merging, the location of the new access point is chosen as follows. After removing the access point pair, it is calculated which receiver points do not receive a sufficient power from the remaining access points anymore: these receiver points will not obtain the requested coverage anymore and they are collected in a set L. We now want to cover all these points by placing a new transmitter with a transmit power that is as low as possible (for the purpose of a low exposure). To find the location for this access point with a minimal power, we apply the following algorithm. For each possible access point location, the algorithm first determines all path losses between that location and the locations of the other receiver points of L. Then, the maximum value of these path losses is stored for each possible access point location. The access point (location) that has the *lowest* stored maximum path loss value will now be able to cover L with the lowest possible transmit power, and hence, also the lowest exposure.
3) In a third phase, it is checked if an access point can be removed by increasing the transmit powers of surrounding access points. The access points serving the least amount of grid points are first investigated, because these have the largest chance to be 'redundant' when small power increases are applied to the surrounding access points. The procedure of increasing the transmit powers of surrounding access points is executed as follows. First, the grid points that lose coverage by removing the access point are determined. After removal of the access point, each of these grid points will have a 'received-power deficit' of a few dB, i.e. the best serving remaining transmitter will provide the grid point with a received power that is a few dB too low to obtain the required coverage. The maximum value of the deficits over all grid points without coverage determines the necessary power increase of a first surrounding access point. After increasing the power of this access point, the size of the set of grid points that have lost coverage will decrease, due to some grid points 'regaining' coverage. As long as this set is not empty, the transmit power of *other* surrounding access points is increased. Due

to the nature of the algorithm, the consecutive power increases will decrease. An access point of which the power has already been increased, is excluded from further power increase operations, because for a low exposure, it is better to have a homogeneous distribution of (low) transmit powers than to have several high and several low transmit powers. This way, the coverage gaps are filled with the lowest possible exposure increase.

4) In the fourth phase, it is investigated if the transmit power of the individual access points can be lowered without losing coverage. Access points with the highest transmit power are first investigated, because with respect to the global exposure value, it is more advantageous to lower these first. The algorithm allows setting a lower limit for the transmit power (e.g., 1 dBm) to conform to the access point configuration settings that are possible.

IV. Application of exposure minimization algorithm

Two scenarios will be considered for the exposure minimization. In a first scenario, we will illustrate the four optimization phases (see Section III-B) for a WiFi network for a throughput of 54 Mbps. In a second scenario, the influence of the required throughput on the obtained field strength distribution will be assessed. Fig. 1 shows the ground plan of the office building for which human exposure will be minimized. For both scenarios, a certain coverage will have to be provided throughout the entire building, except in the rooms that are crossed out (see Fig. 1). These rooms are kitchens, storerooms, elevator shafts,... All coverage calculations are based on the specifications of a WiFi 802.11 b/g reference receiver. Access points are always placed at a height of 200 cm above ground level and the receiver is assumed at a height of 100 cm above ground level. The minimization is performed using the metric E_M (see Section III-A).

A. Scenario 1: exposure minimization phases for a homogeneous WiFi network (54 Mbps)

In the first (homogeneous) scenario, WiFi access points are placed over the entire building floor in order to provide coverage for HD video streaming (54 Mbps). The four exposure minimization phases described in Section III-B are applied. Table I lists the results of each of the phases.

In phase 1, the WHIPP optimization module places access points on the ground plan, with the empty ground plan of the considered building floor as an input to the algorithm. 23 Access points with an EIRP of 1 dBm are needed, yielding a median electric-field strength E_{50} of 0.053 V/m and a 95%-percentile value E_{95} of 0.190 V/m. E_M equals 0.122 V/m. The plan on top of Fig. 1 shows the result of phase 1 for the considered building floor after this first optimization phase, i.e. optimal network design with only access points with an EIRP of 1 dBm.

In phase 2, access point pairs are merged. The six access point pairs that are circled in the top design of Fig. 1, can be merged with a resulting lower global exposure E_M (see Section III-A). Fig. 1 shows the resulting network after the second optimization phase (middle ground plan). The newly placed access points are indicated with an arrow in Fig. 1 and have EIRPs between 0 and 3 dBm. Although coverage is now provided with a lower number access points (17 (with EIRP between 1 and 3 dBm) instead of 23 (with EIRP of 1 dBm)), the E_{50} and E_{95} values also decrease, to respective values of 0.049 V/m and 0.174 V/m. E_M decreases from 0.122 V/m to 0.112 V/m.

In a third phase, it is investigated if access points can be removed by increasing the transmit power of the surrounding access points in an optimal way. This would e.g., be the case if there is one access point that is more or less circularly surrounded by other access points that are within a reasonable distance from the middle transmitter. Removing the middle access point while increasing each (or some) of the powers of the surrounding access points with a few dB could then 'fill' the coverage gap that arose in the middle by removing the (middle) access point. For the building floor under test however, no access points can be removed, due to the 'homogeneous' distribution of the access points over the building floor. By a homogeneous distribution, we mean that each of the access points covers a substantial and more or less equal part of the coverage area.

In the final phase 4, transmit powers are lowered where possible. For the investigated building floor, it is possible to lower the EIRP of six access points without losing the requested coverage. It is allowed to decrease the EIRP of the access points circled in the bottom ground plan of Fig. 1, from 1 dBm in the middle network design to 0 dBm in the bottom network design. Final E_{50} and E_{95} values are 0.047 V/m and 0.164 V/m, E_M decreases further to 0.106 V/m.

Traditionally, network designers try to provide coverage with the least amount of access points possible. With 'traditional' network design, we mean a design that provides network coverage with as few access points as possible. Obviously, the access points will then transmit at the maximally allowed power. For the considered building configuration, a network with (three) access points with an EIRP of 20 dBm is designed. The exposure values for a 'traditional' network design of the investigated building are compared with the four exposure optimization phases in Table I. Compared to the traditional deployment, the final exposure-optimized network (after phase 4) has a median exposure that is reduced by almost 60% and a 95%-percentile value that is reduced by more than 70%. Also the standard deviation σ of the electric-field strengths on the building floor is noticeably higher for the traditional deployment. The exposure-optimized network causes a lower and more homogeneous field strength distribution.

It should be noted though, that in real-life network deployments, the total installation and operational cost will often be an important factor in the design of the network. 17 Access points are required for our exposure-optimized network, almost six times as much as for the traditional design.

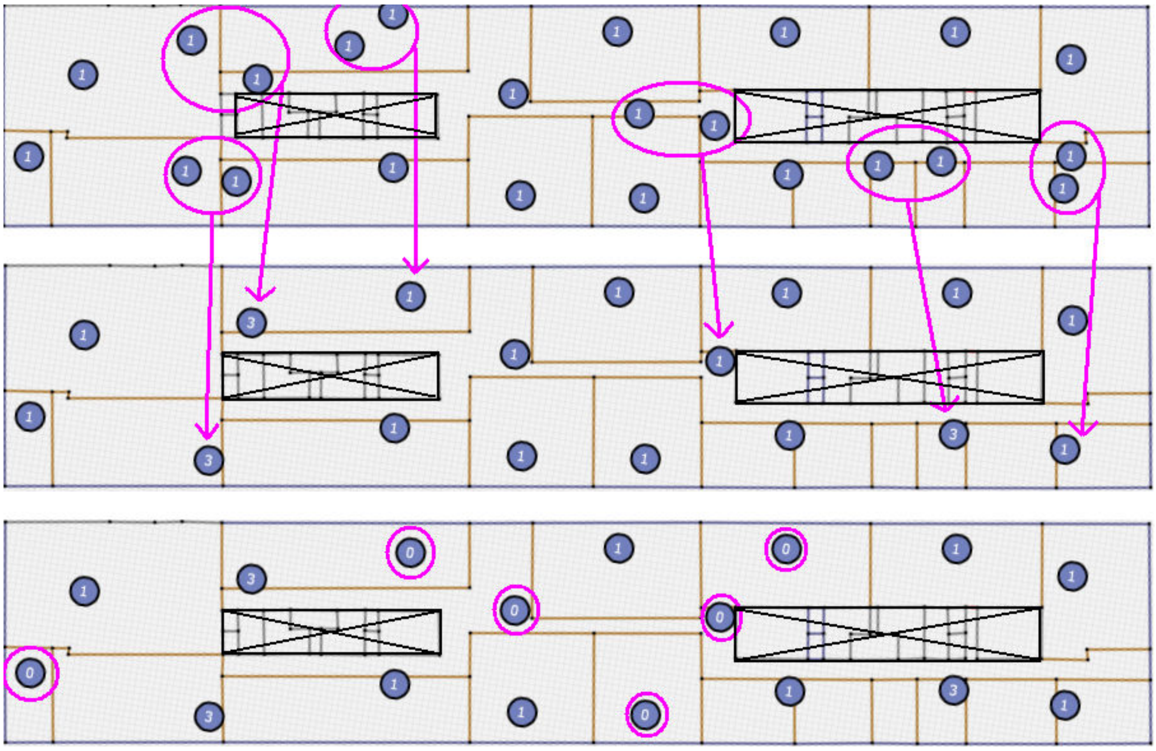

Fig. 1. Network layout after first (top figure, circles indicate mergeable access point pairs), second (middle figure, arrows indicate newly placed access points), and final (bottom figure, circles indicate APs with lowered EIRP) exposure minimization phase. (AP = dot, EIRP is indicated within dot, the crossed out parts of the building do not require coverage.)

Case	#APs [-]	EIRP [dBm]	E_{50} [V/m]	E_{95} [V/m]	σ [V/m]	E_M [V/m]
After phase 1	23	1	0.053	0.190	0.071	0.122
After phase 2	17	1 to 3	0.049	0.174	0.069	0.112
After phase 3	17	1 to 3	0.049	0.174	0.069	0.112
After phase 4	17	0 to 3	0.047	0.164	0.067	0.106
Traditional	3	20	0.114	0.558	0.295	0.336

TABLE I
NUMBER OF ACCESS POINTS (#APS) AND THEIR EIRP NEEDED TO COVER THE BUILDING FLOOR OF FIG. 1 AND RESULTING MEDIAN (E_{50}) AND 95%-PERCENTILE (E_{95}) EXPOSURE VALUES FOR THE DIFFERENT OPTIMIZATION CASES FOR A WIFI NETWORK PROVIDING A THROUGHPUT OF 54 MBPS.

The exposure-optimized network not only has a higher cost, but also a higher energy consumption. An optimal network planner should decide on a trade-off between cost, energy consumption, and exposure.

B. Scenario 2: comparison of traditional vs. exposure-optimized deployment for different throughputs in a homogeneous WiFi network

In the previous section, a homogeneous WiFi network providing a throughput of 54 Mbps is investigated. However, it is expected that the provided throughput on the building floor will have a huge influence on the field strength distribution. In this (homogeneous) scenario, we will therefore assess the influence of the required throughput requirement (varying from 6 to 54 Mbps) on the electric-field strength distribution and the network design and we will make a comparison of a traditional network design and an exposure-optimized network design. Table II summarizes the number of access points (#APs) and their EIRP needed to cover the building floor of Fig. 1 and the field strength distribution parameters (median (E_{50}), 95%-percentile (E_{95}), E_M, and standard deviation σ) for a traditional network deployment (EIRP of 20 dBm) and the exposure-optimized deployment (according to the algorithm of Section III-B, after phase 4). Table II shows that for lower throughputs, the building floor can be covered with a substantially lower number of access points. E.g., the exposure-optimized network requires 17 access points for a throughput of 54 Mbps, while for a throughput of 6 Mbps, only two access points are needed.

Fig. 2 shows the cumulative distribution functions of the electric-field values on the building floor of Fig. 1 for different throughputs for the traditional network deployment vs. the exposure-optimized network. Fig. 2 and Table II show that for lower throughputs, also the field strength values decrease, as expected. The median (E_{50}) and 95%-percentile (E_{95}) drop, from 0.047 V/m and 0.164 V/m respectively, to 0.007 V/m and 0.053 V/m respectively. Of course, for all investigated throughputs, the exposure-optimized networks cause noticeably lower field strengths on the building floor. Fig. 2 and Table II

TP [Mbps]		#APs [-]	EIRP [dBm]	E_{50} [V/m]	E_{95} [V/m]	σ [V/m]	E_M [V/m]
54	**trad.**	3	20	0.114	0.544	0.194	0.329
	opt.	17	0 to 3	0.048	0.169	0.067	0.108
36	**trad.**	2	20	0.045	0.386	0.144	0.236
	opt.	7	-1 to 4	0.025	0.102	0.035	0.065
24	**trad.**	1	20	0.034	0.277	0.102	0.176
	opt.	5	-2 to 1	0.017	0.075	0.026	0.047
18	**trad.**	1	20	0.034	0.277	0.102	0.176
	opt.	4	-1 to 1	0.013	0.073	0.026	0.043
12	**trad.**	1	20	0.034	0.277	0.102	0.176
	opt.	3	-4,1,3	0.011	0.062	0.022	0.039
6	**trad.**	1	20	0.034	0.277	0.102	0.176
	opt.	2	-1,2	0.007	0.050	0.018	0.030

TABLE II
NUMBER OF ACCESS POINTS (#APS) AND THEIR EIRP NEEDED TO COVER THE BUILDING FLOOR OF FIG. 1 AND RESULTING MEDIAN (E_{50}), 95%-PERCENTILE (E_{95}), AND GLOBAL (E_M) EXPOSURE VALUES AND STANDARD DEVIATIONS σ FOR DIFFERENT INTENDED THROUGHPUTS (TP) FOR A TRADITIONAL NETWORK DEPLOYMENT (TRAD.) VS. AN EXPOSURE-OPTIMIZED NETWORK DEPLOYMENT (OPT.).

show that the exposure-optimized network for 54 Mbps has a similar median (E_{50}) value as the traditional deployment for 36 Mbps. However, the exposure-optimized network has a more homogeneous field distribution (steeper slope of the cdf for optimal design in Fig. 2, lower E_{95} and σ in Table II). For the different throughputs, the reduction of E_M when switching from a traditional deployment to an optimized deployment is at least 67.2% (0.108 V/m vs. 0.329 V/m, for 54 Mbps).

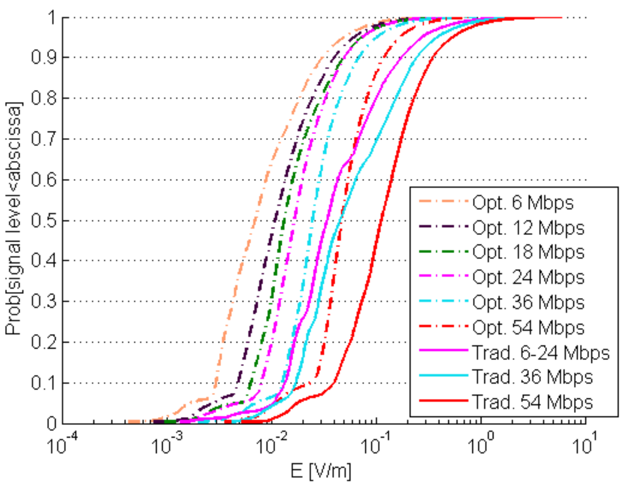

Fig. 2. Cumulative distribution function of electric-field values on the building floor of Fig. 1 for different throughputs for the traditional network deployment vs. the exposure-optimized network (Opt. = exposure-optimized network, Trad. = traditional network design).

V. CONCLUSIONS

A heuristic indoor network planner for exposure calculation and minimization in WiFi networks is developed. The validated model for the electric-field strength in the vicinity of an AP is presented. An exposure minimization algorithm is presented and applied to a WiFi network, using a simple but accurate metric. Depending on the intended throughput, field strength reductions of at least 67.2% and large increases in the homogeneity of the field strength distribution on the building floor are obtained, compared to traditional network deployments.

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